(4)

AD-A200 267

OFFICE OF NAVAL RESEARCH

Effect of Finite Size on Magnetoresistance

by

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Prepared for Publication

in

Physical Review B

Departments of Chemistry and Physics
State University of New York at Buffalo
Buffalo, New York 14260

October 1988

88 1012 057

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION Unclassified		1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY		3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE		
4. PERFORMING ORGANIZATION REPORT NUMBER(S) UBUFFALO/DC/88/TR-86		5. MONITORING ORGANIZATION REPORT NUMBER(S)

6a. NAME OF PERFORMING ORGANIZATION Depts. Chemistry & Physics State University of New York	6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code) Fronczak Hall, Amherst Campus Buffalo, New York 14260		7b. ADDRESS (City, State, and ZIP Code) Chemistry Program 800 N. Quincy Street Arlington, Virginia 22217

8a. NAME OF FUNDING/SPONSORING ORGANIZATION Office of Naval Research	8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER Contract N00014-86-K-0043

8c. ADDRESS (City, State, and ZIP Code) Chemistry Program 800 N. Quincy Street Arlington, Virginia 22217	10. SOURCE OF FUNDING NUMBERS			
	PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)
Effect of Finite Size on Magnetoresistance

12. PERSONAL AUTHOR(S)
H.R. Lee, H.G. Oh and Thomas F. George

13a. TYPE OF REPORT	13b. TIME COVERED FROM _____ TO _____	14. DATE OF REPORT (Year, Month, Day) October 1988	15. PAGE COUNT 17

16. SUPPLEMENTARY NOTATION   Prepared for publication in Physical Review B

17.	COSATI CODES		18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	MAGNETORESISTANCE, DISORDERED FINITE SIZE EFFECTS, CONDUCTIVITY METALLIC SYSTEM QUANTUM CORRECTIONS

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

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20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified	
22a. NAME OF RESPONSIBLE INDIVIDUAL Dr. David L. Nelson	22b. TELEPHONE (Include Area Code) (202) 696-4410	22c. OFFICE SYMBOL

DD Form 1473, JUN 86   Previous editions are obsolete.   SECURITY CLASSIFICATION OF THIS PAGE

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Abstract

Finite size effects are studied for magnetoresistance in a disordered metallic system. Quantum corrections to the conductivity are strongly affected by the presence of an in-plane magnetic field in a thin film. They are also affected significantly by the boundaries of the finite quantum size. Expressions are obtained for the quantum correction to the conductivity due to both effects. The dephasing characteristic time scale due to the magnetic field is found by the exact eigenvalues of the system. One-, two- and three-dimensional results can be obtained with the proper limits. Some numerical results are presented for the given inelastic scattering length.

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I. Introduction

The effect of a magnetic field on electronic states has been studied extensively for disordered systems.[1-3] The predictions of the anomalous magnetoresistance have been tested by several experiments on metal films[4] and semiconductor structures.[5] The resistance of thin films and wires has been studied in the presence of a longitudinal magnetic field,[3] which is more effective than a field directed perpendicular to the film. In Ref. 3, the dimensions of the system are very small compared to the magnetic length because the magnetic field is treated as a small perturbation. Here perturbation theory yields the dephasing characteristic time $\tau_H - 12a_H^2/DW^2$ for a square film or a wire of rectangular cross section, where a_H is the magnetic length of a particle with charge 2e, D is the electon diffusion coefficient, and W is the dimension of the system. Generally perturbation theory can be used when the condition $W \ll a_H$ holds. But, it is not appropriate to apply perturbation theory to the ground state, which is most important for corrections to the conductivity. The reason is explained later in this paper. Here we study the effect of the boundaries on the eigenvalues of the maximally crossed diagram in a thin film or wire with the longitudinal magnetic field by a numerical method. From the eigenvalues of the maximally crossed diagram, we obtain analytical expressions for quantum corrections to the conductivity of thin films and wires, which are given in Eqs. (13) and (14), respectively. Quantum corrections to the conductivity are calculated as a function of the normalized dimension (W/a_H) of the thin film or wire. Since a wide range of the normalized dimension W/a_H is used in our calculations, the actual dimension W of the system can range from

very small values to values which are larger than the magnetic length. We obtain the dephasing characteristic time $\tau_H \sim 24\, a_H^2/DW^2$ as different from the result of the perturbation method in restricted geometries.

II. Theory

The quantum correction to the conductivity of non-interacting electrons weakly scattered by rigid random impurities is

$$\Delta\sigma(\omega \to 0) = -\frac{se^2}{\pi\hbar}\, D\Gamma(\vec{r},\vec{r}',\omega) \quad , \tag{1}$$

where s is spin degeneracy, and $\Gamma(\vec{r},\vec{r}',\omega)$ is the vertex correction due to the sum of all the maximally crossed diagrams. In the absence of the magnetic field, the vertex part $\Gamma(\vec{r},\vec{r}',\omega)$ is

$$\Gamma(\vec{r},\vec{r}',\omega) = \frac{1}{\hbar} \sum_{\vec{q}} \frac{1}{Dq^2+i\omega} \quad . \tag{2}$$

This vertex part is strongly affected by the presence of an external magnetic field, because the symmetries inherent to the system are broken by the field. This has been studied in Ref. 1 in the coordinate representation through the equation

$$\hbar[D(-i\frac{\partial}{\partial\vec{r}} - \frac{2e}{\hbar c}\vec{A}(\vec{r}))^2 + \frac{1}{\tau_{in}}]\,\Gamma(\vec{r},\vec{r}') = \delta(\vec{r}-\vec{r}') \quad , \tag{3}$$

where $\vec{A}(\vec{r})$ is the magnetic vector potential, and $-i\omega$ is replaced by the inelastic scattering time τ_{in}^{-1} at finite temperature.[6]

Now let us consider a thin film which has a thickness W under an in-plane magnetic field $\vec{H} = (0,0,H_0) = \vec{\nabla} \times \vec{A}$. If we choose the Landau gauge $\vec{A} = (0, xH_0, 0)$, the solution of Eq. (3) can be written as

$$\Gamma(x,x') = \int \frac{dq_y dq_z}{(2\pi)^2 \hbar} \sum_n \frac{\psi_{n,q_y}(x)\psi_{n,q_y}(x')}{D\{q_z^2 + E_n(q_y)\} + \frac{1}{\tau_{in}}} \quad , \tag{4}$$

where $\psi_{n,q_x}(x)$ and $E_n(q_y)$ are the eigenfunctions and eigenvalues, respectively, of the equation

$$- [\frac{\partial^2}{\partial x^2} - (q_y - \frac{2e}{\hbar c} H_0 x)^2] \psi_{n,q_y}(x) = E_n(q_y)\psi_{n,q_y}(x) \tag{5}$$

within the film. The above equation can be written as

$$- [\frac{\partial^2}{\partial x^2} - \frac{(x-x_0)^2}{a_H^4}] \psi_{n,q_y}(x) = E_n(q_y)\psi_{n,q_y}(x) \quad , \tag{6}$$

where $a_H = \sqrt{\frac{c\hbar}{2eH_0}}$ is the magnetic length of a doubly-charged particle and x_0 is related to the wavevector q_y by the expression $x_0 = a_H^2 q_y$. Now if we introduce the normalized coordinate $\xi = \sqrt{2}x/a_H$, Eq. (6) can be transformed into the well-known Weber equation,

$$[\frac{\partial^2}{\partial \xi^2} - \frac{1}{4}(\xi - \xi_0)^2 + (\nu_n + \frac{1}{2})]\psi_{\nu_n, q_y}(\xi) = 0 \quad , \tag{7}$$

where ξ_0 is related to the wavevector q_y by $\xi_0 = \sqrt{2}a_H q_y$. We construct the general solutions of Eq. (7) as

$$\psi_{\nu_n, q_y}(\xi) = A \, D_{\nu_n}(\xi) + D \, D_{\nu_n}(-\xi) \quad , \tag{8}$$

where A and B are the normalization constants and $D_m(z)$ is the Weber function given by

$$D_m(z) = 2^{m/2} \exp(-\frac{z^2}{4}) \left[\frac{\sqrt{\pi}}{\Gamma(-\frac{m}{2}+\frac{1}{2})} \, {}_1F_1(-\frac{m}{2}; \frac{1}{2}; \frac{1}{2}z^2) \right.$$

$$\left. - \frac{\sqrt{2\pi} \, z}{\Gamma(-\frac{m}{2})} \, {}_1F_1(-\frac{m}{2}+\frac{1}{2}; \frac{3}{2}; \frac{1}{2}z^2) \right] \quad . \tag{9}$$

Here ${}_1F_1(a;b;x)$ is the confluent hypergeometric function[8] and $\Gamma(z)$ is the gamma function. The eigenvalues are given by

$$E_n(q_y) = \frac{2}{a_H^2} (\nu_n + \frac{1}{2}) \quad . \tag{10}$$

III. Results and Discussion

Equation (7) yields the discrete spectrum of eigenvalues for each value of the continuously varying wavevector q_y. If there are no boundaries, both

the eigenvalues and eigenvectors become identical to the solutions describing the unrestricted motion of free particles in the magnetic field. The eigenvalues of Eq. (7) can be determined if the precise form of the confining potential is given. The results are shown in Fig. 1 for normalized dimensions of the sample $\sqrt{2}W/a_H = 1.0$ with the boundaries of an infinite confining potential barrier, given by

$$\frac{\partial \psi_{n,q_y}(x)}{\partial x} \Bigg|_{x=\pm\frac{W}{2}} = 0 \quad . \tag{11}$$

Since each mode in Fig. 1 shows parabolic-like behavior as a function of the wavevector q_y, we may write the eigenvalues in a parabolic approximation as

$$E_n(q_y) = \frac{\Delta_n}{a_H^2} + C_n q_y^2 \quad , \tag{12}$$

where Δ_n is the y-intercept ($q_y = 0$) and C_n represents the coefficient of the quadratic term in each mode.

For a thin film, when we substitute Eq. (12) into (4) and integrate over q_y and q_z, we obtain

$$\Delta\sigma = \frac{e^2}{2\pi^2\hbar} \sum_n \frac{1}{\sqrt{C_n}} \ln\left(\frac{1/\ell_{el}^2 + 1/\ell_{in}^2}{\Delta_n/a_H^2 + 1/\ell_{in}^2}\right) \quad , \tag{13}$$

where the elastic diffusion length $\ell_{el} = \sqrt{D\tau}_{el}$ is used for the upper limit of the integration. The quantum corrections to the conductivity of rectangular wires with transverse dimensions small in comparison with ℓ_{in} can be obtained in the same way and are given by

$$\Delta\sigma = -\frac{2e^2}{\pi^2 \hbar} \sum_n \frac{1}{\sqrt{C_n(\frac{1}{\ell_{in}^2} + \frac{\Delta_n}{a_H^2})}} \tan^{-1}\left[\frac{C_n(1/\ell_{el}^2 - \Delta_n/a_H^2)}{1/\ell_{in}^2 + \Delta_n/a_H^2}\right]^{\frac{1}{2}} . \qquad (14)$$

Numerical results for magnetoconductivity in thin films and the magnetoconductivity per unit length in rectangular wires are presented in Figs. 2 and 3, respectively, for various values of the ratio W/ℓ_{in}. In each graph we have used the unitless quantity $\xi = \sqrt{2}W/a_H$ in the x-direction, and the dimensions of the sample are normalized to the inelastic scattering length ℓ_{in}. Thus x-coordinates of the graphs are proportional to $\sqrt{H}_0$ for the given sample size. The effect of a magnetic field becomes more prominant on the quantum interference (weak localization) at small values of W/ℓ_{in}, that is, at small dimensions of the sample or at large values of ℓ_{in}(low temperature) for the given system.

The values Δ_0 and C_0 of the lowest-lying state (n=0), which is the most important for quantum corrections to the conductivity, are given in Table I for comparison with those in the absence of a magnetic field. Without the magnetic field, $E_n^0(q_y)$ may be written in a similar form as

$$E_n^0(q_y) - (\frac{n\pi}{W})^2 + q_y^2 \quad , \tag{15}$$

where $n - 0, \pm1, \pm2, \ldots$. When the condition $W \ll a_H$ holds, Table I shows $\Delta_0/a_H^2 - W^2/24a_H^4$ for the ground state, whereas perturbation theory yields $W^2/12a_H^4$. As we can see clearly from Eq. (5) that perturbation theory can not be applied for small values of $q_y \approx 0$, which has the most significant contributions to the corrections to the conductivity. Thus the characteristic time scale must be $\tau_H - 24a_H^2/DW^2$ in magnetoconductivity, which is given by

$$\sigma(H) - \sigma(0) - \frac{e^2}{2\pi^2 \hbar} \ell n(\frac{\tau_{in}}{\tau_H} + 1) \tag{16}$$

for a thin film, and the quantum corrections to the conductivity per unit length are given by

$$\Delta\sigma(H) - - \frac{e^2}{\pi \hbar} (\frac{1}{D\tau_{in}} + \frac{1}{D\tau_H}) \tag{17}$$

for a wire of rectangular cross section.

If the other condition $W \gg a_H$ holds, the eigenvalues are divided into two parts: (1) the surface part, that is, those states whose orbit is affected by one wall of the sample, and (2) the bulk orbits which are not affected by the boundaries of the sample. The surface part always has an almost constant contribution to the conductivity, whereas the bulk part is proportional to the sample width W due to many degenerate states in each

level. Thus, we can recover the results of the bulk limit given in Ref. 1 (cf. the values in Table I).

References

1. B. L. Al'tshuler, D. Khemel'nitzkii, A. I. Larkin, and P. A. Lee, Phys. Rev. B $\underline{22}$, 5142(1980)

2. P. A. Lee and T. V. Ramakrishnan, Rev. Mod. Phys. $\underline{57}$, 287 (1985).

3. B. L. Al'tshuler, and A. G. Aronov, JETP Lett. $\underline{33}$, 499 (1981).

4. J. J. Lin, and N. Giordano, Phys. Rev. B $\underline{33}$, 1519 (1986); S. Wind, M. J. Rooks, V. Chandrasekhar and D. E. Prober, Phys. Rev. Lett. $\underline{57}$, 633 (1986).

5. R. G. Wheeler, K. K. Choi, A. Goel, R. Wisnieff and D. E. Prober, Phys. Rev. Lett. $\underline{49}$, 1674 (1982); T. J. Thornton, M. Pepper, H. Ahmed, D. Andrews and G. J. Davies, ibid. $\underline{56}$, 1198 (1986)

6. D. J. Thouless, Phys. Rev. Lett. $\underline{39}$, 1167(1977); P. W. Anderson, E. Abrahams and T. V. Ramakrishnan, Phys. Rev. Lett. $\underline{43}$, 718 (1979).

7. P. M. Morse, and H. Feshbach, Methods of Theoretical Physics (McGraw-Hill, New York, 1953), p. 1403.

8. M. Abramowitz, and I. A. Stegun, Handbook of Mathematical Functions, (Dover, New York, 1964), p. 503.

TABLE I. Eigenvalue shift (Δ_0) and parabolic coefficient (C_0) due to the boundaries and the longitudinal magnetic field.

$\xi(W)$	1.0×10^{-4}	1.0×10^{-3}	1.0×10^{-2}	0.1	1.0	2.0	3.0	4.0
Δ_0	4.167×10^{-9}	4.167×10^{-7}	4.167×10^{-5}	4.167×10^{-3}	4.165×10^{-2}	1.656×10^{-1}	3.631×10^{-1}	6.018×10^{-1}
C_0	1.000	1.000	1.000	1.000	0.992	0.912	0.797	0.687

TABLE I. Eigenvalue shift (Δ_0) and parabolic coefficient (C_0) due to the boundaries and the longitudinal magnetic field.

$\xi(W)$	1.0×10^{-4}	1.0×10^{-3}	1.0×10^{-2}	0.1	1
Δ_0	4.167×10^{-9}	4.167×10^{-7}	4.167×10^{-5}	4.167×10^{-3}	4.165
C_0	1.000	1.000	1.000	1.000	0.

Figure Captions

1. The energy dispersion in a longitudinal magnetic field with dimensions of the system $\frac{\sqrt{2}W}{a_H} = 1.0$ and infinite-barrier confining potential. The x-coordinate ξ_0 is related to the wavevector q_y by $\xi_0(q_y) = \sqrt{2}a_H q_y$.

2. The magnetoconductivity (divided by the coefficient $\frac{e^2}{2\pi^2 \hbar}$) of a thin film plotted against the unitless parameter $\xi(a_H) = \frac{\sqrt{2}W}{a_H}$. (1) $W/\ell_{in} = 0.05$, (2) $W/\ell_{in} = 0.2$ and (3) $W/\ell_{in} = 1.0$.

3. The magnetoconductivity (divided by the coefficient $\frac{2e^2 \ell_{in}}{\pi^2 \hbar}$) per unit length of a rectangular wire plotted against the unitless parameter $\xi(a_H) = \frac{\sqrt{2}W}{a_H}$. (1) $W/\ell_{in} = 0.05$, (2) $W/\ell_{in} = 0.2$ and (3) $W/\ell_{in} = 1.0$.
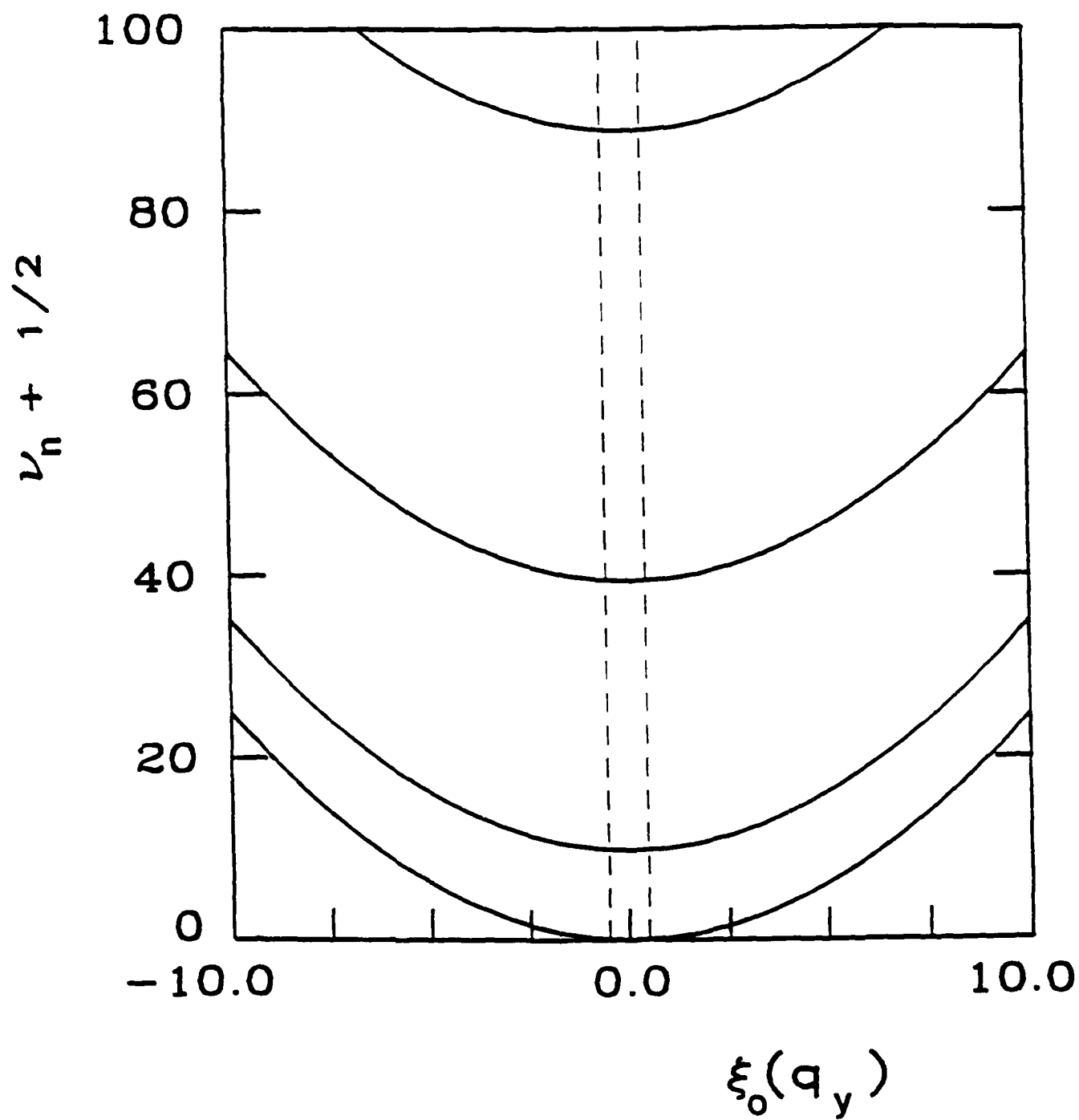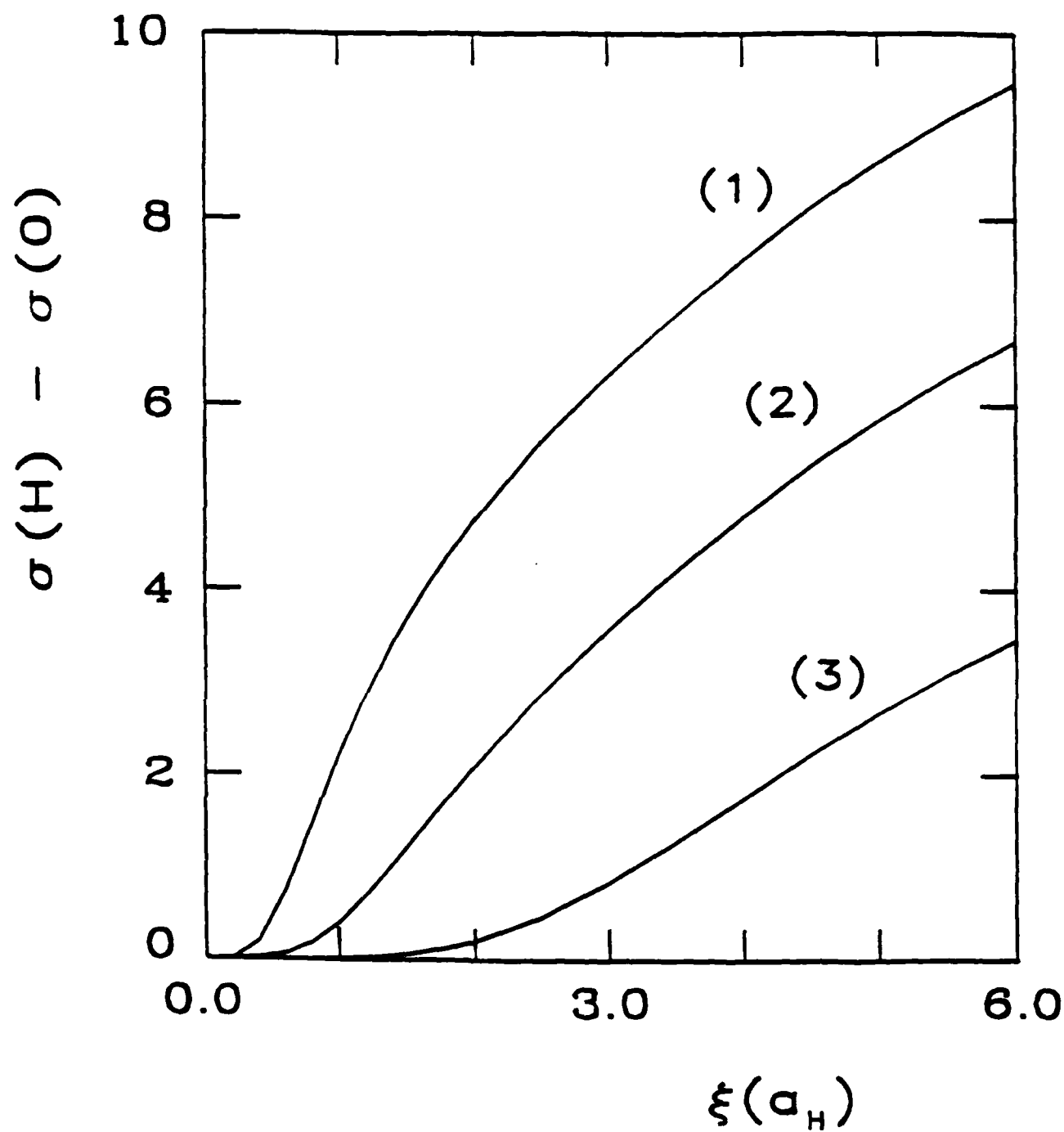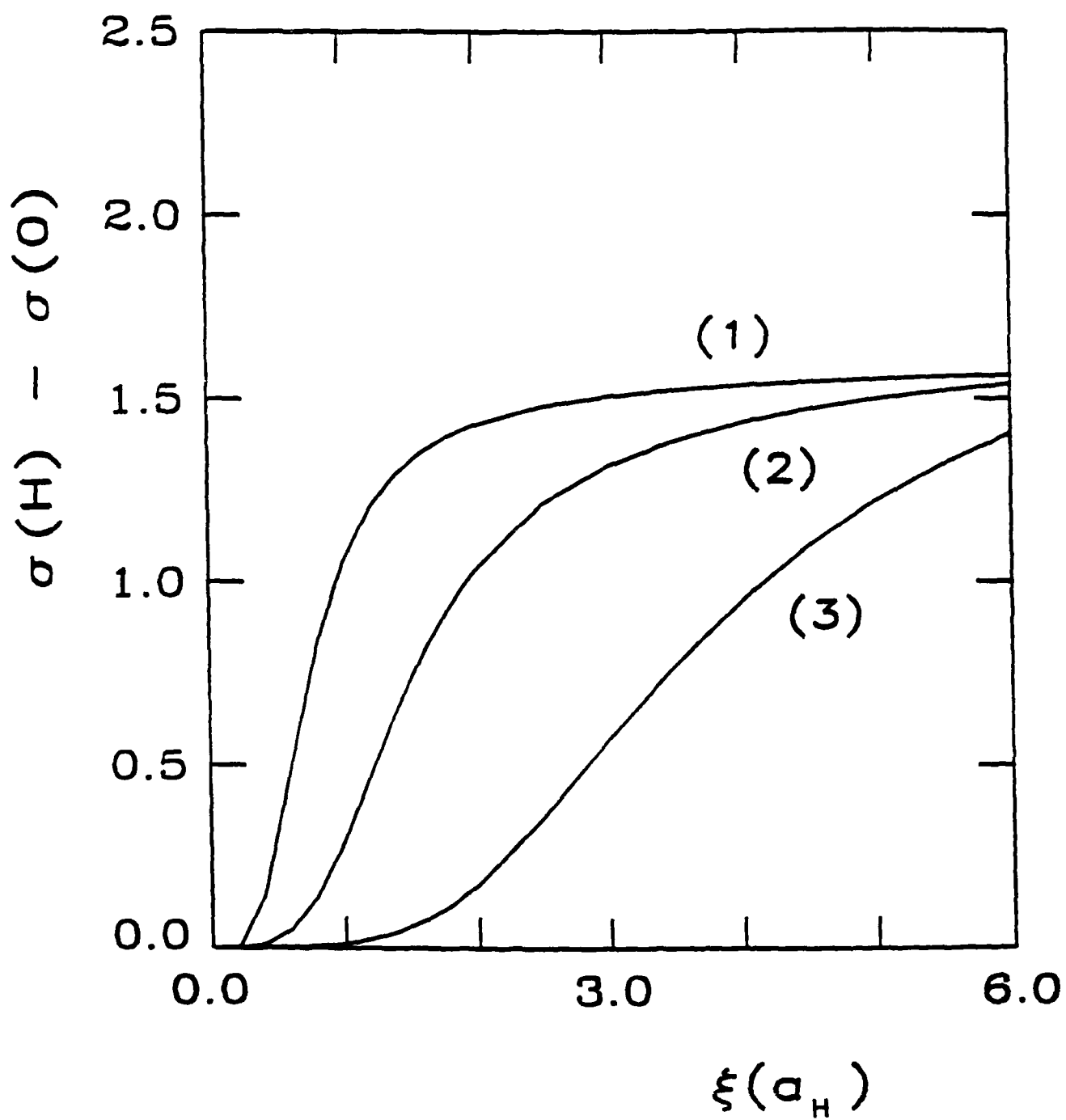
Fig. 1

Fig. 2

Fig. 3

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